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Energy policy tools for agricultural residues utilization for heat and power generation: A case study of sugarcane trash in Thailand

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ABSTRACT

Cane trash could viably substitute fossil fuels in heat and power generation projects to avoid air pollution from open burning and reduce greenhouse gas (GHG) emission. It is competitive with bituminous and other agro-industrial biomass. Using cane trash for heat generation project could provide a higher reliability and return on investment than power generation project. The heat generation project could be viable (Financial Internal Rate of Return, FIRR = 36–81%) without feedstock subsidy. With current investment and support conditions, the capacity of 5 MW option of power generation project is the most viable (FIRR = 13.6–15.3%); but 30 MW, 1 MW and 10 MW options require feedstock subsidy 450–1100 Baht/t-cane trash to strengthen financial viability. Furthermore, the revenue from carbon credit sales could compensate the revenue from current energy price adder and increases 0.5–1.0% FIRR of power generation project. Using cane trash for 1 MW power generation could reduce GHG emission 637–861 t CO_2eq and avoid air pollutant emissions of 3.35 kg nitrogen oxides (NO_x), 0.41 kg sulfur oxides (SO_x) and 2.05 kg volatile organic compounds (VOC). Also, 1 t steam generation from cane trash could avoid pollutant emissions of 0.6 kg NO_x, 0.07 kg SO_x, and 0.37 kg VOC. The potential of cane trash to cause fouling/slagging as well as erosion are not significantly different from other biomass, but chlorinated organic compounds and NO_x could be higher than bituminous and current biomass feedstock at sugar mill (bagasse and rice husk).

Contents

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1. Introduction

In sugarcane production, pre-harvest and post-harvest burning are general worldwide practice for cane harvesting. Pre-harvest sugarcane burning facilitates manual harvesting to quickly cutting and pilling of sugarcane so that the labor could obtain larger amount (weight) for a higher daily wage. Cane field burning destroys soil organic matter and soil microbial those are useful to maintain good soil properties such as air permeability, water-holding property and cation exchange capacity [1]. Besides loss in soil quality, other consequence drawbacks affect cane feedstock quality for sugar mills such as loss in commercial cane sugar (CCS) in the range of 0.35–1.32% [2] and high impurities from burnt residues and planting material [3]. Burnt cane loses ~2.5% of weight and ~3% of sugar content more than those from unburnt cane within 9 days and rapidly loss after 17 days [1,4]. Post-harvest is done to facilitate land preparation, get rid of weed and protect fertilizer loss due to bud sprouting before cultivation period [4]. Both pre/post harvest burning are causing severe air pollution for over 10 years. Airflow from cane leaves burning contained 17% respirable size fraction (<4 μm in diameter) and potentially harmful cristobalite that could pose a higher risk to respiratory effects [5,6]. On the other hand, there are many efforts to stop causing this pollution from private sector and government as well as government promotion for biomass utilization. Furthermore, a worldwide interest on utilizing cane trash as a fuel for heat and power generation is increasing with promising technologies. It could be possible to implement for the other areas that have the same problems (see more details about situation in Thailand and worldwide experiences on using cane trash as a fuel instead of open burning in the online Supplementary text).

Pollution from cane trash burning in field is addressed as problem to be solved. The pollution could be avoided when the cane trash could be utilized. Cane trash can substitute fossil feedstock to be used as fuel for heat or power generation that contributes to greenhouse gas (GHG) emissions reduction. Therefore, "Changing pollution from cane burning to Bioenergy" is addressed as solution. This research presents evaluation of agricultural residues potential for heat and power generation based on sustainable utilization in a national scale and proposes scheme of policy tools; cane trash in Thailand is used as a case study. For more realistic potential evaluation, cane trash utilization for heat and power generation is considered in both dimensions of the utilization system and competitive utilization systems. Viability of utilization considers linkage of four aspects, resource availability, technological viability, environmental and socio-economic viability. The same approach and policy scheme could be applied to the other agricultural residues.

2. Methodology

The pollution from open burning could be avoided if the cane trash could be utilized for heat or power generation. Also the cane trash could substitute fossil feedstock and contribute to GHG emissions reduction. Since the GHG emissions could be claimed as certified emission reduction (CER) or carbon credit and sold for monetary profit. Therefore, utilization of cane trash for heat and power provide both environmental benefit and economic value. Positioning of the cane trash feedstock in the system boundary is defined. Since bagasse is byproduct from cane milling process, almost sugar mills use bagasse as main fuel for both steam and power generation; whereas the other biomass (such as rice husk and wood residues) is used as supplementary fuel. Therefore, cane trash could also be used as a supplementary fuel for sugar mill and should be compete with the supplementary fuel.

In the overall procedure as shown in the Fig. 1, potential of cane trash utilization considers in two dimensions, horizontal and vertical. Horizontal dimension considers cane trash in heat and power generation system from upstream to downstream. Vertical dimension considers cane trash in comparison with other competitive alternatives, including feedstock alternatives for heat and power generation or fuel-related problems, utilization alternatives for maintaining food security and soil nutrient (see detailed description in the online Supplementary material). A system approach to developing and implementing a potential evaluation consists of the following steps including the aspects of resource, technology, environment and socio-economic. (1) *Resource–technology*: potential technologies as well as fuel related problems in the process of cane trash utilization for heat and power generation are reviewed. Available cane trash resource is evaluated against requirements of technology for resource–technological viable options; (2) *Resource–technology–environment*: air pollution and global warming potential (GWP) from implementing the resource–technological viable options is evaluated; (3) *Resource–technology–environment–economic*: on the basis of the resource–technological viable options, deduction of air pollution and global warming potential (GWP) is evaluated for potential environmental benefit; (4) *Evaluation of socio-economic viability*: the viable options in the aspects of resource–technology–environment from previous step are evaluated for socio-economic viability which is final integration of all aspects. Finally, strength, weakness, opportunity, threat and influential factors are analyzed for suitable energy policy tools (see detailed methodology in online Supplementary text).

3. Result and discussion

3.1. Potential of heat and power technology for cane trash utilization

3.1.1. Cane trash utilization for heat and power generation in other countries

Today, many mature heat and power technologies using the 1st generation biomass (agro-industrial biomass) have been being generally used in many countries. As increase of a worldwide interest on using the 2nd generation biomass (post-harvest residues), many mature technologies are ready to apply for utilization; however, cane trash is not yet being widely used. Cane trash is mostly found to be used as supplementary fuel for stoker boilers, using with bagasse [7–11]. Based on pilot scale, operating spreader fire stoker boiler with non–pretreated cane trash can cause high level of slagging and fouling, but the chemical elements to cause slagging and fouling could be reduced by water leaching and significantly reduced by small particle feedstock size [12]. Co-firing cane trash and other biomass (bagasse, wood chips, and coconut) with bituminous coal in a 19 MW travelling grate boiler was found to have the capability to reduce both nitrogen oxides (NO_x) and sulfur oxides (SO_x) compared with original coal-fired power plants [13].

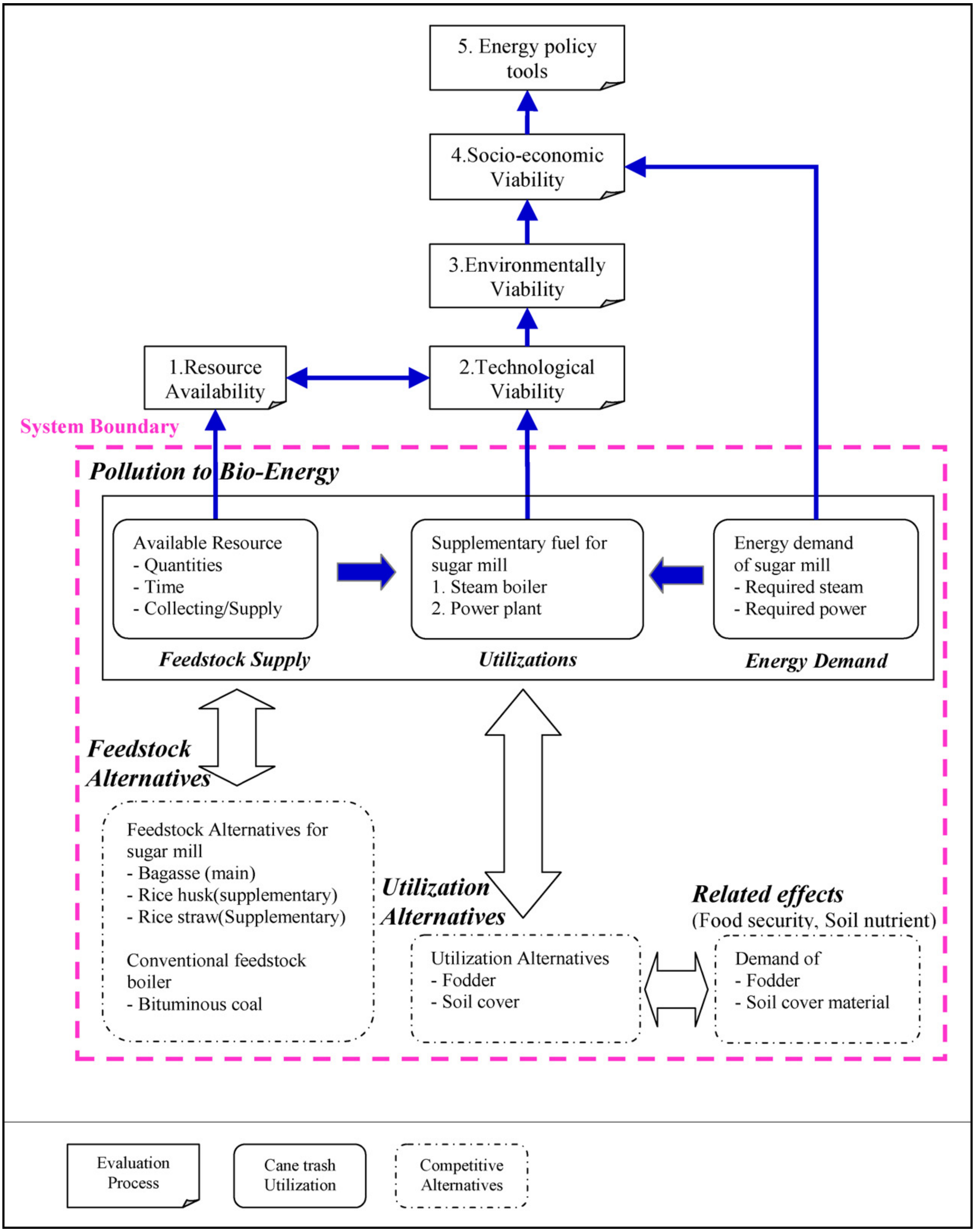

Fig. 1. Overall research procedures.

3.1.2. Available heat and power technologies for biomass utilization in Thailand

Current heat and power technologies in Thailand apply conventional thermochemical conversion. Industrial steam boilers are mostly operated with stokers while power plants are operated with direct combustion, fluidized beds, and gasification. Compared to fluidized beds, stoker boilers are flexible for partial load operations, less sensitive to slagging/fouling and more economical for smaller capacities. Stoker boilers are the conventionally successful technology for heat and power with efficiencies of 70%–80% together with several applications of grate stokers, fixed grates, travelling grates and vibrating grates. Grate stokers are more flexible as to fuel types and particle sizes, and less sensitive to slagging/fouling. It has been in widespread use for a long time with lower costs for investments

and operations. Moreover, local manufacturers and maintenance companies are available in Thailand [14–16]. Spreader fired stokers provide higher efficiencies of 80–90%. Partial load operations are also possible and have a lower cost for capacities over 20 MW. In contrast, fluidized beds provide higher heat transfers, more flexibility in fuel sizes and moisture content, and have lower NO_x formation, but they are difficult to control with partial load operations [17]. On the other hand, gasification provides higher efficiency from converting synthesis gas to power; it requires a gas engine for power generation and can be implemented for small capacities. However, it requires tar and ash removal for maintenance [18]. The boiler technology must be selected to satisfy power plant requirements in terms of capacity, investment efficiency and operating costs. Advantages and disadvantages of fuel could affect the operating performance and the operating costs (see details of power project option and industrial boiler option in online Supplementary text).

3.1.3. Plant operating problems due to fuel properties

Cane trash has not yet been commercially used as a feedstock for heat and power generation in Thailand; nevertheless, there are many current heat and power technologies using biomass that could possibly use cane trash economically and increase incentives for farmers to collect it. Also cane trash supply systems are under research in Thailand and proven for possibility [19]. Chemical composition in biomass can cause operating problems that affect plant availability and reliability; also equipments and method for treatment can lead to additional expense. Therefore, fuel properties should be taken into consideration for viability of biomass utilization. The main problems of biomass combustion are slagging, fouling, corrosion, erosion and NO_x emissions. Since cane trash is never used for steam and power generation, the plant operating problem due to fuel properties is considered as comparable with current biomass (bagasse and rice husk) using in steam plant and power plant and other lignocellulosic biomass (wheat straw and rice straw, switch grass) which have properties similar to cane trash.

During combustion, ash deposition on the heating surface could take place in two ways, slagging and fouling. Slagging is the formation of molten or partially fused deposits on furnace walls or convection surfaces exposed to radiant heat. Fouling is defined as the formation of deposit on convection heat surfaces such as superheaters and reheaters. High alkali content could potentially cause slagging, fouling and grate sintering. Slagging and fouling could be reduced by keeping the operating temperature under 760 °C whereas grate sintering could be controlled by mixing with low alkali fuel (to dilute alkaline content). High chlorine (Cl) content could potentially cause fouling and hot corrosion requiring on-grate chlorine capture. Excess combustion air and temperatures higher than 760 °C could also result in the formation of chlorinated organic compounds and NO_x [20]. Rice husk, rice straw and wheat straw contain silicon dioxide (SiO_2) which could result in high quartz ashes that can cause erosion problems in the convective pass of the boiler and handling system [20,21].

The slagging index, $R_s < 0.6$ indicates low potential of slagging and fouling index, $R_f < 0.2$ indicates low potential of fouling [22]. Thus cane trash has very low potential to cause slagging ($R_s = 0.058$–0.045) and not significant potential to cause fouling ($R_f = 0.15$–0.20). Slagging from cane trash is lower than wheat straw but not significantly different than switch-grass those are currently used in European countries. It is also significantly lower than bituminous coal which is currently used for industrial boiler. In comparison with bagasse which is mainly used at sugar mill, cane trash tends to cause slightly higher slagging but much lower fouling. Nevertheless, it does not significantly cause both slagging and fouling compared to rice husk and rice straw which are competitive supplemental feedstock alternatives at the sugar mill. The potential of cane trash to cause fouling/slagging as well as erosion are not significantly different from other biomass. However, chlorinated organic compounds and NO_x could be higher than bituminous and current biomass feedstock using at the sugar mill (bagasse and rice husk) but less than rice straw. Therefore, combustion air and operating temperature should be controlled to limit the NO_x formation and hot corrosion.

Ash of cane trash is a byproduct of heat or power generation. It would bring additional profit if it could be utilized and sold. SiO_2 in the fly-ash could be utilized as a cement additive and fly ash from the co-firing of biomass-coal is acceptable for used; however, fly ash from the mixing of many types of biomass could negatively impact concrete properties [14]. Rice husks are currently used as fuel and ash is collected for producing a pozzolan in the cement industries [23]. Cane trash also has a high SiO_2 content (64%–67%) as compared to other biomass (rice husk 91%, rice straw 75%, wheat straw 55%, switch grass 65%, bagasse 47%) [24,25] that could be possible to be used in this way.

3.2. Implementable capacity and contribution of GHG emissions reduction

3.2.1. Resource availability and opportunity of utilization

Sugarcane in Thailand have been cultivated in 47 provinces of four major regions, almost sugarcane quantities are supplied for the sugar mills and about 4% is reserved for breeding [26]. Meanwhile, 46 sugar mills were installed in these regions, the larger-capacities sugar mills are installed in the larger cane production area [27]. Total available cane trash from sugarcane production is around 5.9 Mt, northeastern provinces (2.34 Mt) and central provinces (1.93 Mt) have larger amount of cane trash than northern provinces (1.32 Mt) and eastern province (0.34 Mt) with average transport distance 20–50 km. Cane trash has not been used as fuel. Current cost is still very high, 1200–1600 Baht/t, there is no incentive to invest for cane trash collecting [28]. Nevertheless, the cane trash supply would be cost effective if sugar mill could arrange collecting and supply instead of directly purchasing from distributor. Cane trash is collected and formed by straw baler, the cane trash bales are manually loaded to truck and delivery to sugar mill. The supply cost is 1,128 Baht/t with new rectangular-bale-forming baler, 1442 Baht/t with 2nd hand rectangular-bale-forming baler, 1444 Baht/t with new cylindrical-bale-forming baler and 1506 Baht/t with 2nd hand cylindrical-bale-forming baler at transport distance 20 km [19]. However, cylindrical-bale-forming baler is bigger and more expensive than rectangular-bale-forming baler, and not widely used in Thailand. Therefore, the cane trash supply cost 1128 Baht/t is the most possible case with currently available machines.

Since sugar mill uses cane as feedstock for sugar production, it also requires steam for cane milling and electricity for plant utility. Most sugar mills currently use bagasse as the main fuel feedstock for steam (85–90% of total fuel feedstock), the other agro-industrial wastes are used as supplementary feedstock, such as rice husk and wood residues. All the 46 sugar mills require 79–101 Mt-steam/y or 30–38 GJ_h/y for cane milling. The available cane trash based on cane utilization at the sugar mills is sufficient for steam generation, that is around 90% of required steam for cane milling (71–89 Mt-steam/y or 28–34 GJ_h/y). This is almost similar amounts to steam (29 Mt-steam/y or 76 GJ_h/y) generated from the available resource (cane trash based on sugarcane production report [26]) within each region as shown in the Fig. 2. Therefore, the available cane trash resource could be used as fuel feedstock for steam or power generation at the sugar mill. Also, it would be more convenient to develop cane trash utilization at these sugar mills for steam and power generation based on the same supply chain as the sugarcane rather

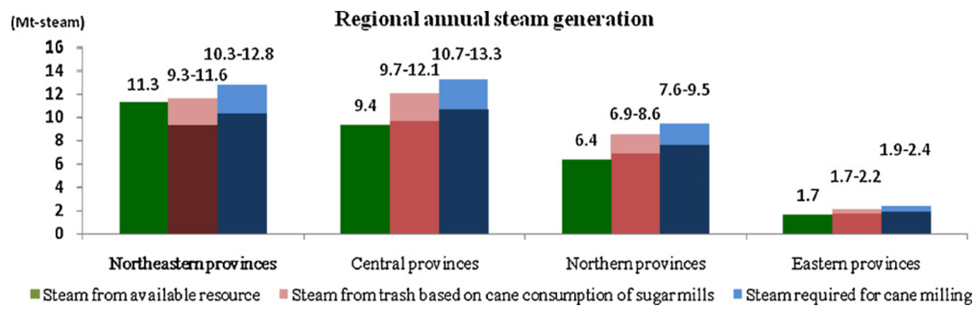

Fig. 2. Regional annual steam generation.

than developed the new supply chain; unless the new supply chain could return the more benefit incentive.

On the other hand, cane trash in Thailand have potential for power generation around 775 MW (20 GJ_e), northeastern provinces 306 MW (7.7 GJ_e), eastern provinces 253 MW (6.4 GJ_e), central provinces 172 MW (4.3 GJ_e) and northern provinces 45 MW (1.1 GJ_e). As seen in Fig. 3, cane trash in these provinces have potential to implement power project with provincial capacity up to 69 MW, <1 MW (VSPP, 5 provinces), 1–10 MW (VSPP, 24 Provinces) and >10 MW (SPP, 18 provinces).

Besides, cane trash could be either incorporated into soil to return soil nutrient or used as cattle fodder. However, soil incorporation requires suitable machine with cost and spend longer time for land preparation than trash burning where only 30–50% of the cane trash is sufficient to maintain the organic content of the soil [10]. Cane trash has much lower nutrient value (4–6% of proteins) and deteriorates over the shorter time than conventional fodder such as grass [29]. Therefore it does not have competitive advantages over conventional fodder and cannot be competitive fodder alternative. Since both utilizations are not proven very convenient and cost effective, also trash can be removed up to 50% without leaving behind any negative effect on soil quality [30,31]. Furthermore, using for heat and power generation could avoid trash burning and its bad effects without reducing soil nutrient. Therefore, using cane trash for heat and power generation does not decrease soil quality compare to the conventional practice (trash burning) and does not affect food (fodder) security.

3.2.2. Air pollution and GHG emissions reduction

Life cycle emissions of cane trash utilization for heat and power generation could avoid air pollutant emissions, especially around 30–70 $\mu g\, m^{-3}$ particulate matter (PM_{10}) during open burning released into the atmosphere, also significantly reduce GHG emissions from fossil energy. 1 t-steam generation from cane trash could avoid pollutant emissions of 0.6 kg NO_x, 0.07 kg. SO_x, and 0.37 kg volatile organic compounds (VOC). Also 1 kWh electricity generation from cane trash could avoid pollutant emissions of 3.35 g NO_x, 0.41 g SO_x and 2.05 g VOC. Cane trash could be implemented with CER from significant CO_2eq emissions reduction 247–250 $kgCO_2$eq/t-steam or 94.53–102.68 t CO_2eq/TJ_h from fuel switching (from coal to cane trash) for heat generation at transport distance 20–150 km (the longer distance provide the lower CER). Cane trash could be implemented with CER from significant CO_2eq emissions reduction from the power project, 637–654 kg/MWh in case of the capacity range 1–10 MW and 835–861 kg/MWh in case of 30 MW or the larger capacity at transport distance 20–150 km (the longer distance provide the lower CER) as shown in the Table 1. Emissions from power plants are correlated with power plant efficiency, transport distances and fuel consumption from different vehicle options, but these do not significantly affect emissions reduction. The lower plant efficiency contributes to the higher emissions, but avoids the higher emissions from open burning because of the higher cane trash consumption. Also the longer transport distance contributes to the higher emissions. Emissions from heat and power plants are correlated with the plant efficiency and fuel consumption from different transport distances, but these do not significantly affect GHG emissions reduction. It is because the baseline emissions (grid emissions from fossil fuel and cane trash open burning) are significantly larger (~122 times) than GHG emissions from the power generation life cycle.

3.3. Opportunity for heat and power generation using cane trash

3.3.1. Competitiveness of using cane trash for heat and power generation

Compared to other fuels, cane trash can substitute for fossil feedstock, in heat and power generation and tends to be competitive with other biomass. By generating costs of 233–311 Baht/t-steam, 1.2–1.6 Baht/kWh at supply cost 1128–1506 Baht/t trash, cane trash is competitive with fossil feedstock, bituminous (392–393 Baht/t-steam, 1.15–1.16 Baht/kWh), natural gas (~807 Baht/t-steam, ~2.24 Baht/kWh) and other biomass (348–377 Baht/t-steam, 1.77–1.92 Baht/kWh) such as saw dust, woodchips and palm shells. Especially, it quite competitive with rice husks (298–348 Baht/t-steam, 1.52–1.77 Baht/kWh) and wood chips (~362 Baht/t-steam, 1.54 Baht/kWh) those are being used in sugar mill. Since the plant efficiency of using cane trash tends to be lower than using rice husks and woodchip; meanwhile cost of rice husk and wood chip is becoming higher because of the higher demand. Therefore, cane trash could produce more incentive than rice husks and woodchip when supply the cost is reduced.

3.3.2. Effects of government supports and carbon credit sales

From financial internal rate of return (FIRR) and economic internal rate of return (EIRR) of the seven scenarios of power projects, power projects without support (S0) is not financially viable (FIRR = 1%–6%) but still has very high EIRR (24%–30%), exception of combustion 5 MW (FIRR = 7.4%, EIRR = 37%); while the other project scenarios with additional supports/benefits have greater FIRR (8–20%). Power project scenarios are compared. The project with current government supports (BS) has 5.5–7.6% greater FIRR than S0 (BS-S0). The project with only subsidy (S4) has lower viability than projects with only energy price adder (S3) that could affect the low viability capacity plants (1 MW and 10 MW). It is proved that current energy price adder is necessary for supporting power projects even the projects sell carbon credits. Carbon credit sales could increase FIRR by 3.7–5.1% over the cases without carbon credit sales (S3-BS, S5-S1); thus, revenue from carbon credit sales could replace revenue from current energy price adder (but not including subsidy) with increasing 0.5–1.0% FIRR. Government support could be possible in terms of financing and promotion for carbon credit selling (i.e. Clean Development Mechanism project development).

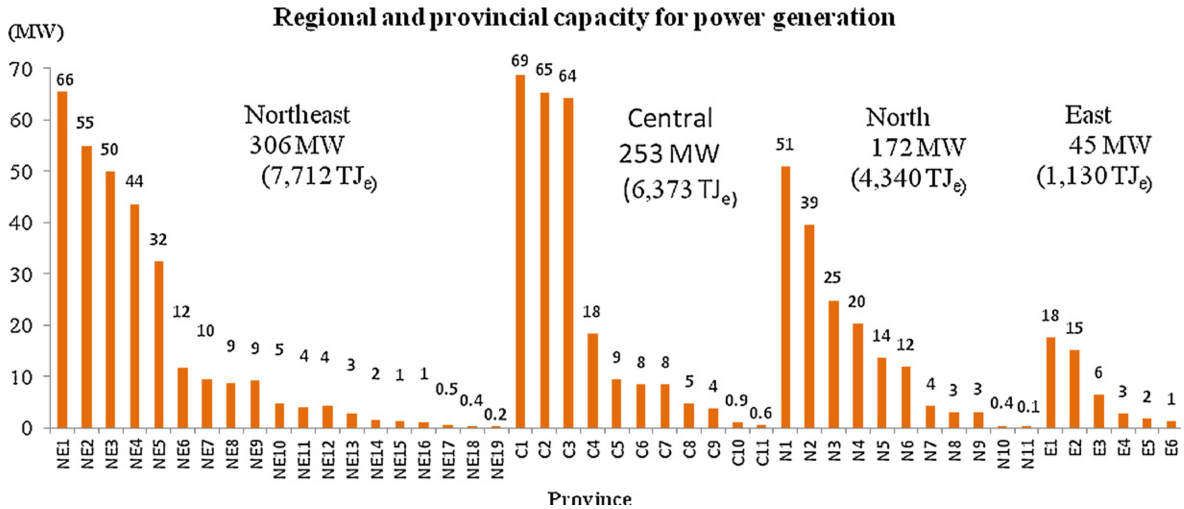

Fig. 3. Regional and provincial capacity for power generation.

3.3.3. *Sensitivity (SI) and risk tolerance (RT)*

In the case of heat generation project, FIRR is more sensitive to plant availability (SI = 4.6) than to cane trash supply cost (SI = 2.1) whereas it is not sensitive to CER price (SI ≈ 0). The risk tolerance on plant availability for heat generation project is very high (79%), only ~21% (operating1650 h out of 8000 h) of plant availability could maintain the project viability. The risk tolerance on fuel supply for heat generation project is not very high (44%), cane trash supply cost should be lower than 2017 Baht/t (transport distance less than 132 km). However sensitivity drastically increases when plant availability is lower than 18% and cane trash supply cost is higher than 1700 Baht/t. Cane trash has higher risk tolerance on supply cost than other agro industrial biomass (RT = 10–16%) except rice husks (RT = 66%) that is quite secured for operating heat projects. Natural gas and heavy oil are not viable which are reflected by a negative value for RT; however coal is viable but with low risk tolerance (RT = 5.6%). Therefore, heat generation projects are quite secured to utilize cane trash.

In the case of power generation project, FIRR is relatively less sensitive to CER price (SI = 0–0.1) and high risk tolerance on CER (RT ≥ 46%, Min CER price 0–22 €/t CO_2) as compared to plant availability and fuel supply costs. As seen in Table 2, the project capacity of 5 MW tends to be more secured for operating with a higher risk tolerance and a lower sensitivity than the project capacity of 1, 10, and 30 MW (lower RT, higher SI) in both cases, without carbon credit sales (BS) and with carbon credit sales (S3). With carbon credit sales (S3), the project could reduce sensitivity and increase the risk tolerance on both plant availability and cane trash supply that make 1, 10, and 30 MW more secured. Compared to heat projects, power generation projects have lower risk tolerance on plant availability and fuel supply costs. Therefore, power projects have a lower security for investments than heat generation projects for implementation, both plant availability and fuel supply cost should be well controlled for operation. The capacities 1, 10, and 30 MW are low security options that should be implemented with carbon credit sales to improve project security.

3.3.4. *Socio-economic viability of heat and power projects and policy tools*

Socio-economic viability of the heat and power generation project considers possible capacity options with transport distances and compare with fossil fuel and competitive biomass. Socio-economic viability is assessed and indicated as FIRR/EIRR and financial/economic payback period (FPBP/EPBP), i.e. a project is viable when FIRR ≥ Weight Average Cost of Capital (WACC) and EIRR ≥ 11% [32–34]. The power project model is set as five possible cases and financial/economic viability is observed for the opportunity of investors and the government on the power projects.

Table 1
Implementable capacity and transport distance.

FIRR/max supply cost[a]	With energy price adder[b] Power					Without energy price adder Heat
	Gasification		Combustion			Combustion
	1 MW	5 MW	5 MW	10 MW	30 MW	20–300 t-steam/h
FIRR	6.4%	13.6%	15.3%	4.9%	8.4%	81%
Max supply cost (Baht/t)	1028	1564	1732	953	1231	2018

Transport distance	Cost[c]	FIRR with feedstock subsidy[d]					
<20 km	1128	3.6–11.8%	8.8–17.9%	9–17.2%	2.4–12%	5.9–14.7%	115–165%
<50 km	1692	NA–5.1%	NA–10.5%	NA–10.9%	NA	NA–9.9%	72–122%
<100 km	2256	NA[e]	NA	NA	NA	NA	27–79%
<150 km	2820	NA	NA	NA	NA	NA	NA–34%

[a] Max supply cost: maximum supply cost to satisfy viability criteria at base scenario; viability criteria: FIRR = WACC (7.6% gasification for power generation, 7.3% combustion for power generation, 8.2% combustion for heat generation).
[b] Energy price adder: 0.3 Baht/kWh.
[c] Cane trash supply cost at base scenario: 1128 Baht/t.
[d] Feedstock subsidy: 450–1100 Baht/t–cane trash.
[e] NA, not available.

Table 2
Sensitivity and risk tolerance of influential factors.

Cane trash supply cost (Baht/t)							
Power project	Base case[a]	BS[b]			S3[c]		
		|SI|[d]	Max[e]	RT	|SI|	Max	RT
Gasification 1 MW	1128	1.71	1028[f]	9%	1.90	1349[f]	−20%
Gasification 5 MW	1128	2.52	1564	−39%	3.50	1923	−70%
Combustion 5 MW	1128	3.10	1732	−46%	4.20	2091	−74%
Combustion 10 MW	1128	1.80	953[f]	16%	2.20	1321[f]	−17%
Combustion 30 MW	1128	3.30	1231[f]	−9%	4.50	1703	−51%
Plant availability (%)							
Power project	Base case	BS			S3		
		|SI|	Min	RT	|SI|	Min	RT
Gasification 1 MW	70%	2.80	74%[g]	−5%	2.90	63%	10%
Gasification 5 MW	70%	2.30	54%	23%	2.40	45%	35%
Combustion 5 MW	80%	2.18	54%	33%	2.20	45%	44%
Combustion 10 MW	80%	1.38	106%[g]	−33%	1.34	63%	21%
Combustion 30 MW	80%	2.60	72%	10%	2.70	49%	39%

[a] Base case: 70%, 80% (plant availability of 1 and 5 MW and 10 and 30 MW), 1128 Baht/t (cane trash supply).
[b] BS, base scenario conditions.
[c] S3, BS with carbon credit sale.
[d] |SI|, SI of Base case at FIRR = WACC.
[e] Max/min value at FIRR = WACC.
[f] Less than base case.
[g] More than base case.

Heat project has very high viability, FIRR/FPBP (81%/1.24 y) and EIRR/EPBP (390%/~0 y). In case of the power project, Very small power producer (VSPP, 1 and 5 MW) tends to be more financially/economically viable than small power producer (SPP, 10 and 30 MW) and gasification is more viable than direct combustion at 5 MW. The larger capacities tend to have higher potential than the lower capacities based on the same conditions. 5 MW has higher potential than 1 MW and 30 MW has higher potential than 10 MW. By avoiding environmental externalities, EIRR is much greater than 11% whereas FIRR is slightly greater than WACC. Thus, there are chances to transfer social benefits from avoiding externalities to investors for optimizing financial/economic viability to increase financial return.

Analysis scheme of policy tools for agricultural reside utilization for heat and power generation is shown in Fig. 4. Originally, the first generation biomass (agro-industrial biomass) was used to replace fossil fuel for GHG emission reduction with its strength of collecting cost-free; but it has weaker competitive advantages such as lower heating value and lower efficiency in operating the same technology. Thus, financial support was provided to encourage utilization. Open burning could be avoid when the agricultural residues are utilized, thus it is promoted as the second generation biomass to replace or support the first generation biomass for replacing fossil fuel for GHG emission reduction. However, since open burning facilitate harvester to earn more benefit and facilitate farmer for quick land preparation. Furthermore, it has much weaker competitive advantages than the first generation biomass. Therefore, discouraging of agricultural residues open burning and encouraging utilization could be simultaneously promoted, it need more incentive than promotion of the first generation biomass. However, the environmental externalities of this pollution could be avoided when it is utilized for heat/power generation or other possible non-polluting utilization. Therefore, financial support should be provided on the basis of feedstock utilization rather than on the basis of energy price adder. Environmental externalities of open burning are estimated by the penalty rate of 1454 Baht/t-cane trash [35], the penalty could be charged with the same rate based on trash amount by 5844 Baht/ha (935 Baht/rai). Feedstock subsidy should be paid per ton of using (or avoid open burning) cane trash that can stimulate project investment and lead to economic return. Since utilization for heat generation is very strongly viable without support, whereas some options of power project require support, the solution is focused on support for power projects of utilization. Most biomass power projects are using agro-industrial waste at lower cost and being financially supported on energy price adder basis and tax exemption. However, cane trash needs to be collected from fields for utilization that result in higher supply costs than agro-industrial waste which are plant-based and thus more localized.

A suitable feedstock subsidy is determined by optimizing financial and economic viability as shown in Table 3. The higher economic benefit from avoiding environmental externalities (in the form of feedstock subsidy) could be transferred to financial benefits to meet economic/financial criteria (FIRR ≥ WACC, EIRR ≥ 11%). FIRR and EIRR of five possible options on base scenario (at cane trash supply cost 1128 Baht/t) are observed against adjusting feedstock subsidy. The higher viability options (5 MW, 30 MW) could meet financial and economic criteria without subsidy whereas the lower viability options, 1 MW requires subsidy 450–1100 Baht/t-cane trash and 10 MW requires 420–1150 Baht/t-cane trash to meet financial viability (FIRR = WACC) and economic viability (EIRR = 11%). Therefore, a subsidy range of 450–1100 Baht/t-cane trash is selected for optimizing financial and economic viability. In the case of heat generation projects, using cane trash is very cost effective even without subsidies. FIRR (115–165%) of heat generation projects with feedstock subsidies of 450–1100 Baht/t is 35–85% greater than projects without subsidies. Energy price adder in terms of Baht/kWh is equivalent to feedstock subsidy 271 Baht/t-trash (1 MW-gasification and 5 MW-combustion), 275 Baht/t-trash (5 MW-gasification), 278 Baht/t-trash (10 MW-combustion) and 360 Baht/t-trash (30 MW-combustion). The recommended subsidies require additional government expenses; the low viability options (1 MW, 10 MW, 30 MW) obtain more subsidies than the high viability options (5 MW). It maintains social benefits (economic return) and increases financial return of all project options, especially the low viability options. To discourage the open burning of cane trash, a penalty of 5844 Baht/ha (935 Baht/rai) based on environmental externalities should be charged. It is expected that

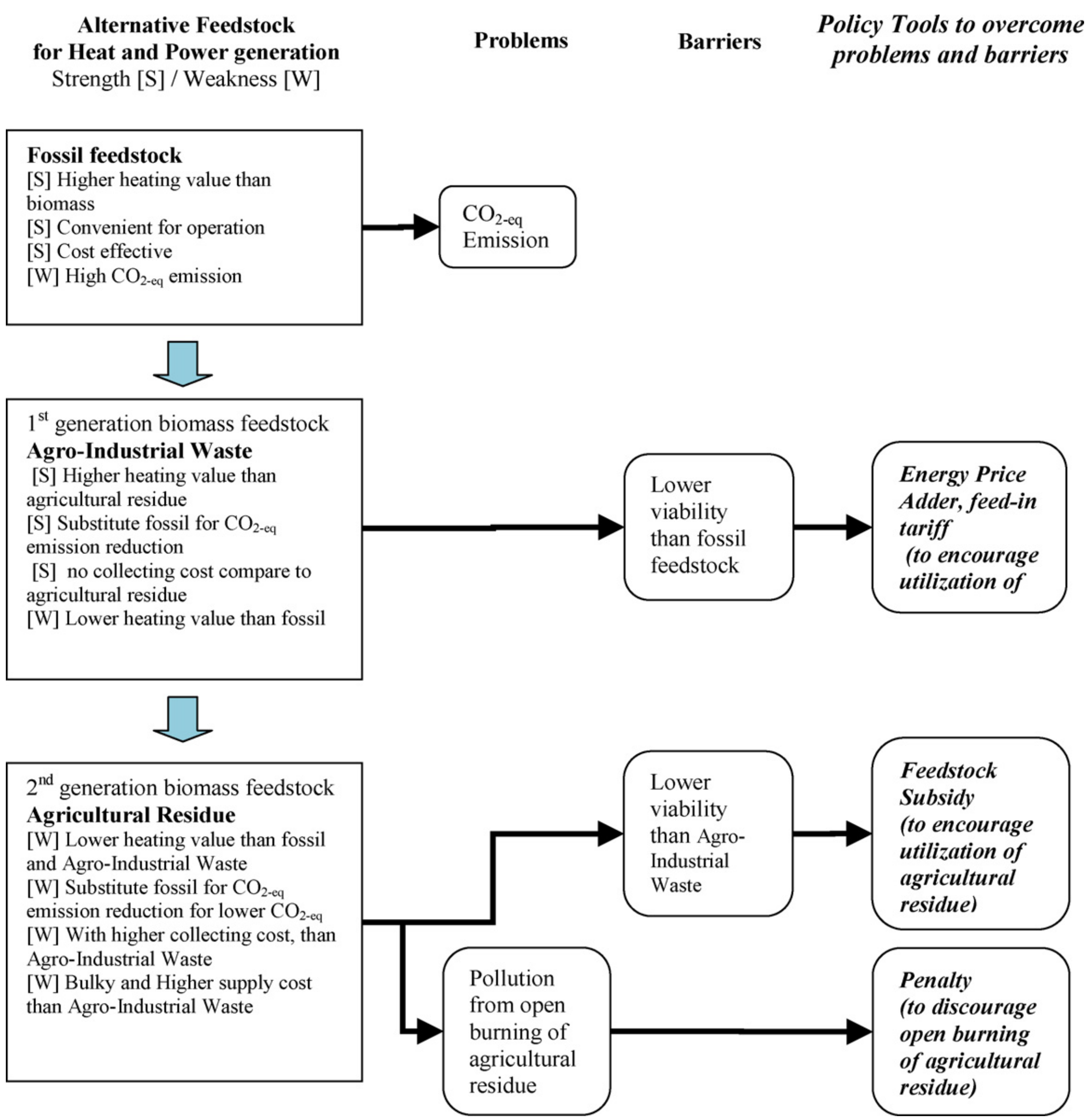

Fig. 4. Analysis scheme of policy tools for agricultural reside utilization for heat and power generation. Power generation is calculated based on fuel consumption at stoker boiler efficiency 19.3%, operating 7008 h. NE, northern province; C, central province; N, northern province; E, eastern province.

this penalty rate is expensive enough to prohibit the open burning, but not for earning benefits.

The shorter supply distances are technically sufficient for the lower capacities; therefore, the average supply cost of lower capacity should be lower than the larger capacities. However, the longer supply distances are tentative options in case the cane trash could be not supplied due to nontechnical reasons. As shown in the Table 3, heat generation project could be viable (FIRR = 36–81%) without feedstock subsidy at the transport distance 20–50 km. In the case of power generation, the capacity 5 MW tends to

Table 3
Range of feedstock subsidy for power generation project.[a]

Technologies/capacities	Without energy price adder at base scenario		With feedstock subsidy			
	FIRR, FPBP	EIRR, FPBP	Subsidy (Baht/t)		Min FIRR	Min EIRR
Gasification 1 MW–SPP	6.4%,	18.2%,	Min	450	7.6%	18.7%
	9.6 y	5.6 y	Max	1100	7.7%	11.0%
Gasification 5 MW–SPP	13.6%,	26.8%,	Min	0	13.6%	26.8%
	6.4 y	3.9 y	Max	2016	33.2%	11.0%
Combustion 5 MW–SPP	14.5%,	28.7%,	Min	0	14.5%	28.7%
	6.3 y	3.7 y	Max	1860	33.2%	11.0%
Combustion 10 MW–SPP	4.9%,	20.2%,	Min	420	7.3%	22.0%
	12.6 y	5.3 y	Max	1150	18.1%	11.0%
Combustion 30 MW–SPP	8.4%,	23.1%,	Min	0	8.4%	23.1%
	9.6 y	4.7 y	Max	970	17.8%	11.0%

[a] Calculation based on base scenario (BS) at cane trash supply cost 1128 Baht/t without consideration of transport distance; viability criteria: FIRR = WACC, 7.1 (gasification), 7.3% (combustion) and EIRR = 11% (gasification/combustion).

be the most feasible options and could implement with highest maximum supply cost with current energy price adder, followed by 30 MW, 1 MW and 10 MW accordingly. The capacity 5 MW-combustion could be viable without feedstock subsidy with higher fuel supply cost, but 5 MW-gasification requires feedstock subsidy $\sim$400 Baht/t-cane trash to be viable. The capacity 1 MW and 10 MW could be viable with feedstock subsidy not less than 1,000 Baht/t-cane trash and less feasible with longer distance than 15 km. The capacity 30 MW could be viable with feedstock subsidy not less than 800 Baht/t-cane trash and less feasible with longer distance than 40 km.

4. Conclusion

In conclusion, this study shows that developing heat and power project using such agricultural residues as cane trash tend to be economically feasible for implementation in Thailand with feedstock subsidy. Also, it is environmentally feasible and satisfies the government's promotion of alternative energy and discouraging cane trash open burning. Supply cost is the main barrier for using cane trash, it is necessary to develop collecting tools to facilitate cane trash harvest as well as supply chain strategies to overcome this barrier. However, fuel related problems require further study in details to ensure operational reliability and improve the plant efficiency for using cane trash in the future. To this end, some demonstration power projects using cane trash should be initiated before promoting it for commercial use.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.rser.2012.02.033.

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